IMproved Assessment of the Greenhouse gas balance of bioeNErgy pathways (IMAGINE)

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Evaluation améliorée des bilans gaz à effet de serre des filières bioénergie

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Livrable D4.1 : GHG balances of bioenergy pathways

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Assessment of biofuel pathways in Ile de France based on ecosystem modelling, including direct and indirect land-use change effects

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1. Abstract

The potential greenhouse gas (GHG) savings resulting from the displacement of fossil energy sources by bioenergy mostly hinges on the uncertainty on the magnitude of nitrous oxide (N_2O) emissions from arable soils occuring during feedstock production. These emissions are broadly related to fertilizer nitrogen input rates, but largely controlled by soil and climate factors which makes their estimation highly uncertain.

Here, we set out to improve estimates of N_2O emissions from bioenergy feedstocks by using ecosystem models and measurements and modeling of atmospheric N_2O in the greater Paris (France) area. Ground fluxes were measured in two locations to assess the effect of soil type and management, crop type (including lignocellulosics such as triticale, switchgrass and miscanthus), and climate on N_2O emission rates and dynamics. High-resolution maps of N_2O emissions were generated over the Ile-de-France region (around Paris) with a generic ecosystem model, O-CN, and an agro-ecosystem model, CERES-EGC, using geographical databases on soils, weather data, land-use and crop management. The models were tested against ground flux measurements, and the emission maps were fed into the atmospheric chemistry-transport model CHIMERE. The maps were tested by comparing the CHIMERE simulations with time series of N_2O concentrations measured at various heights in the planetary boundary layer in two locations in 2007.

The emissions of N_2O, as integrated at the regional scale, were used in a life-cycle assessment of representative biofuel pathways: bioethanol from wheat and sugar-beet (1st generation), and miscanthus (2nd generation process); biodiesel from oilseed rape. Effects related to direct and indirect land-use changes (in particular on soil carbon stocks) were also included in the assessment based on various scenarios and literature references. The potential deployment of miscanthus was simulated by assuming it would be grown on the current sugar-beet growing area in Ile-de-France, or by converting permanent fallow land.

Compared to the standard methodology currently used in LCA, based on fixed emissions for N_2O, the use of model-derived estimates leads to a 10 to 40% reduction in the overall GHG emissions of biofuels. This emphasizes the importance of regional factors in the relationship between agricultural inputs and emissions (altogether with biomass yields) in the outcome of LCAs. When excluding indirect land-use change effects (iLUC), 1st generation pathways enabled GHG savings ranging from 50 to 73% compared to fossile-derived equivalents, while this figure reached 88% for 2nd generation bioethanol from miscanthus. Including iLUC reduced the savings to less than 5% for bio-diesel from rapeseed, 10 to 45% for 1st generation bioethanol and to 60% for miscanthus. These

figures apply to the year 2007 and should be extended to a larger number of years, but the magnitude of N_2O emissions was similar between 2007, 2008 and 2009 over the Ile de France region.

2. Introduction

Controversy is brewing about the greenhouse gas (GHG) intensity of biofuels and bioenergy chains in general (Pimentel, 2003; Kavanagh, 2006). While there appears a consensus on the benefits of displacing fossil fuels with energy from biomass (Hill, 2007; Smith et al., 2007), the reported GHG savings may differ widely for seemingly similar pathways (Quirin et al., 2004). These results are usually based on the life cycle assessment (LCA) methodology, relying the same ISO standards but different calculation hypotheses and scope, in particular regarding coproduct allocation methods, system boundaries, functional unit, or impact characterization. However, correcting for these differences to make these results commensurate only reduces part of their variability (Farrell et al., 2006). In fact, the source of input data used in the inventory step of the LCA plays a major role in its final outcome. In particular, the emissions occurring upon the cultivation of energy crops in the field have a strong influence on the energy and GHG balance of the whole chain. For instance, a study on 1st generation biofuels in France concluded that the selection of emission factors to calculate the efflux of nitrous oxide (N_2O) resulting from fertilizer application could alter the GHG savings by up to 41% for rapeseed methyl ester (ADEME/DIREM, 2002).

In most LCAs of bioenergy chains, N_2O emissions from soils are estimated with fixed emission factors (EFs), expressing a proportionality between N_2O efflux and fertilizer N input rate. These factors have a wide range of uncertainty (Eggleston et al., 2006), and their wordwide median value has even been questioned recently based on the gap between bottom-up inventories of fertilizer-derived field emissions and the atmospheric build-up of N_2O (Crutzen et al., 2008). The higer EFs proposed by the latter authors would negate the GHG benefits of most bioenergy pathways, including 2nd generation biofuels from lignocellulose. It thus appears crucial to obtain more reliable assessments of the level of N_2O emissions attributable to bioenergy feedstock production (Don et al., 2011).

Emissions of N_2O from soils are difficult to assess because they vary widely across time and space (Duxbury and Bouldin, 1982), depending on environmental conditions (soil properties and climate) and agronomic characteristics (such as crop yields and management, or fertilizer use efficiency). Improving their estimation implies taking these drivers explicitly into account, and applying LCA at the supply area level rather than based on notional country- or European-wide 'average' cultivation fields. This stresses the need for developing generic methods with a capacity to address the variability within these feedstock supply areas. Combining experimental monitoring of field-scale emissions with biophysical models appears as a promising avenue to provide reliable estimates of N_2O emissions at a scale relevant for bioenergy units (Gabrielle et al., 2006). However, there has been this far very little work on the comparison of emission maps obtained with such a methodology and integrative atmospheric measurements, such as tower fluxes (Freibauer, 2003). Most of source inversion studies from atmospheric measurements have been carried out at continental to global scales (Denman et al., 2007).

Here, we used improved estimates of N_2O fluxes obtained at regional scale from WPs 1 to 3 of the IMAGINE project as inputs to the LCA of a set of representative biofuel chains, as an improvement over existing LCAs based on fixed emission factors. The following case-studies were investigaed, using Ile de France (ie the domain probed by the atmospheric monitoring and emission maps validation - WP3):

1. biodiesel production from oilseed rape, bioethanol production from wheat and sugar-beet (1^{st} generation biofuels), and miscanthus (via enzymatic hydroloysis of lignocellulose, a

prospective second-generation pathway),
2. combined heat and power from miscanthus and cereal straw.

Emission fluxes were obtained by running the ecosystem models CERES-EGC and O-CN over the feedstock supply area (Ile de France), and a series a historical weather data to capture the effect of inter-annual variability and the long-term effects of perennial crops over their growing cycle (20 years). The effect of feedstock production on soil C balances and dynamics were also be included in the LCA, relative to a reference land-use scenario in the absence of bioenergy production, thus account for direct LUC effects. Indirect LUC was taken into account base on the meta-analysis of De Cara et al. (2011). The consequences of bioenergy feedstock production on soil water evapotranspiration rates were also assessed, among with other LCA impact categories.

3. Methodology

1. Definition of case-studies and pathways

A baseline scenario for LCA calculations were defined based on existing studies in France (ADEME/DIREM, 2010 ; Prieur et al., 2008; Gabrielle and Gagnaire, 2008 ; Gabrielle et al., 2008) or EU level (Reinhardt et al., 2000; EUCAR/CONCAWE/JRC, 2006), for biomass and equivalent fossile pathways. The pathways considered include: 1st generation biofuels from oilseed rape, sugar-beet and winter wheat; combined heat and power from energy crops, and co-products (eg cereal straw); cellulosic ethanol obtained by enzymatic hydrolysis from miscanthus. Feedstock supply area was Ile de France, for which comparisons between ecosystem modelling and atmospheric measurements were available to infer N_2O fluxes. Measurement data on experimental plots were also available for model validation in WP1 for all feedstocks except sugar-beet, for which validation was done in Picardie (Bessou, 2009).

Feedstock	Region	Direct Land-use changes	Indirect Land-use change	End-product
Sugar-beet	Ile de France	None	De Cara et al., 2011	Liquid biofuel (ethanol)
Oilseed rape	Ile de France	None	De Cara et al., 2011	Bio-diesel
Winter wheat	Ile de France	None	De Cara et al., 2011	Bio-ethanol
Miscanthus	Ile de France	Conversion from arable land (sugar-beet)	De Cara et al., 2011	Liquid biofuel (ethanol)
Miscanthus	Ile de France	Use of fallow land	None	Liquid biofuel (ethanol)
Wheat straw	*Ile de France*	*None*	*None*	*Combined heat and power*

Table 1: Feedstock types, regions and pathways considered in the LCA, along with land-use change hypotheses.

Simple assumptions were made for land-use changes (LUC) related to feedstock production (Table 1): no effects of direct LUC for arable crops, which were supposed to be diverted from food to energy uses. For the new energy crop (miscanthus), the assumption was that it displaced sugar-beets and the crops associated in the rotations. This decrease in the acreage of sugar beet is consistent with the observation of recent trends due to the sugar reform (AGRESTE data), and the projections derived at regional level from economic modelling (De Cara and Thomas, 2008). The N_2O and CO_2 balances of crops were simulated in the Ile de France region, assuming it would be the scale for the supply area of biofuel production units, with the two ecosystem models (O-CN and CERES-EGC), with or without bioenergy feedstock production, over a series of climatic years for miscanthus to capture inter-annual variability and long-term trends.

2. Life-cycle inventories

Table 2 summarizes the sources of data used for the various steps of the bioenergy chains. Crop management data were taken from surveys carried out by the French Ministry of Agriculture (AGRESTE ; Boukari, 2010) for arable crops, and expert knowledge as defined in Bessou (2009) for miscanthus in Northern France (Table 3). Yields were obtained from regional simulations by CERES-EGC in 2007, and are compared to the yield statistics reported for this year by AGRESTE in Table 3. The miscanthus yields were calculated as 90% of the peak aerial biomass in autumn, correspond to an early harvest of this crop (Strullu, 2010). The remaining 10% were left as harvest residues.

Processes / stage	Source	References
Feedstock production		
Crop management data (input rates) : - miscanthus - winter wheat - oilseed rape - sugar-beet	 Expert knowledge AGRESTE survey AGRESTE survey AGRESTE survey	 Bessou, 2009 Boukari, 2010 Boukari, 2010 Boukari, 2010
Crop yields		
Machinery & inputs production (fertilizers, pesticides, fuel)	EcoInvent database (v2.0)	
Field emissions		
N_2O emissions	IPCC 2006, CERES-EGC or O-CN simulations	WP2
Other direct Nr losses	CERES-EGC simulations	WP2
Soil C dynamics in relation to LUC	IPCC guidelines or CERES-EGC simulations	WP2
Transport	EcoInvent database	
Conversion to energy		
1^{st} generation ethanol	EcoInvent database, ADEME (2010) & Bessou (2009)	
2^{nd} generation ethanol	EcoInvent database and Bessou (2009)	
Heat and power	EcoInvent database ('cogeneration from wood' process').	

Table 2: Sources of data for the life-cycle inventory of the pathways investigated.

	Winter wheat	Sugar Beet	Oilseed Rape	Fallow	Miscanthus on SB	Miscanthus on fallow
Fertilizer input rates (kg N/P/K ha^{-1})						
Mineral N	200	133	182	0	50	50
P	68.9	70	70	0	2.7	2.7
K		110	50	0	4	4
Pesticide input rates (total, kg a.i. ha^{-1})	1.11	1.42	2.48	0	0	
Number of tractor passages per yr	11.52 h ou 6 passages (*Ecobiom)*	12	14 passages		8.6	
Regional crop yields (t DM/ha^{-1})	7.7[a]	8.5[a]	3.2[a]		14[b]	14[b]
Simulated crop yields (t DM ha^{-1})	7.87 (grains)	10.92 (tubers)	3.09 (grains)		14.9 (aerial DM)	14.4 (aerial DM)

Table 3. Crop management data for the energy crops considered here.

a : from agricultural statistics for 2007.
b : from Carton, 2009

Direct emissions of reactive N (Nr), whether gaseous or leaching, were simulated at regional scale with CERES-EGC for the year 2007, along with C and water balances (Table 4). The predicted Nr losses included: nitrate leaching, emissions of ammonia, nitric oxide and nitrous oxide. For the latter, two other estimates were used: the IPCC 2006 guidelines (IPCC, 2006) following the adapation of ADEME (2010) for application to biofuels in France, and an emission factor of 0.98% derived from O-CN simulations over France (Prieur, 2012).
Arable crops were simulated by CERES-EGC from September 2006 to the end of 2007, to include the sowing of winter crops. Miscanthus was simulated over a 29-year time interval running from 1980 to 2008. Emission fluxes were cumulated over the simulation periods and averaged on a yearly basis for miscanthus.

3. Impact characterisation and interpretation

The CML 2000 method for the characterisation of mid-point impacts was selected (Guinée et al., 2002). The following impact categories were thus assessed : eutrophication, acidification, and photochemical ozone formation, global warming, depletion of abiotic resources.
The uncertainty related to climate variability will be assessed by Monte-Carlo simulations, and the significance of net GHG savings analysed.

4. Results & discussion

1. GHG emissions and LCA of feedstock production

	Winter wheat	Sugar Beet	Oilseed Rape	Fallow	Miscanthus on SB	Miscanthus on fallow
Gaseous losses (kg N ha^{-1} yr^{-1})						
N_2O : CERES-EGC O-CN IPCC	1.76 0.98 2.72	2.56 0.98 2.84	0.82 0.98 2.87	1.95 0.98 0	0.82 0.98	0.68 0.98
NO	1.29	1.22	1.26	1.01	0.41	0.41
NH_3	3.25	3.92	2.34	-0.15	-1.73	-1.62
Nitrate leaching (kg N ha^{-1} yr^{-1})	99.54	99.66	7.76	166.79	20.31	25.21
Drainage (mm yr^{-1})	69.79	74.73	56.14	103.71	338.64	340.08
Soil C stock variations (kg C ha^{-1} yr^{-1})	46.91	48.50	46.24	51.76	46.08	45.42

Table 4. Nr losses and annual evapo-transpiration and drainage for the energy crops. Data for year 2007, except for miscanthus (1980-2008 averages). Variations in soil C stocks are reported over the 29-year simulation period of the miscanthus. Emissions of N_2O are detailed in Table 5.

Table 4 lists the direct emissions of reactive N (Nr), the water balance fluxes and soil organic C variations for the various feedstocks and obtained with the ecosystem model CERES-EGC, or the O-CN, or the ADEME (2010) methodology based on the 2006 IPCC guidelines for N_2O (Tanabe et al., 2006) and agronomic references derived from surveys or expert knowledge for France.

Following the IPCC guidelines' classification, ecosystem models were assumed to predict both direct emissions (related to fertilizer application) and indirect emissions related to the wet and dry deposition of N on the fields, and the fate of crop residues (since simulations encompassed the autumn period following harvest). Direct emissions were averaged over the Ile de France region from the 2007 year-round simulations by CERES-EGC, while for O-CN an emission factor was derived for the whole of France by running the model with and without fertilizer inputs for a reference year (1980). The resulting value was 0.98%, very close to the 1% value recommended in the 2006 IPCC guidelines (Prieur, 2012).
Indirect emissions due to leaching were calculated as 0.75 % of the nitrate leaching, simulated either with CERES-EGC or estimated from ADEME (2010 ; Table 4). In the ADEME methodology, nitrate leaching was given a similar value for most crops. A average value for the whole of France was also given from expert knowledge and surveys for the N content of crop residues, to which a 1% emission factor was applied.

According to the CERES-EGC model, the highest N_2O emissions occurred with the sugar-beet crop due to its being a spring crop with fertilizer applications later into spring than the winter crops, when soil conditions (in particular temperature) are more conducive to denitrification. Surprisingly, fallow soils ranked second after sugar-beet because of the absence of a crop actively taking up soil N in spring. The emissions of miscanthus were 2 to 5-fold lower than the annual crops, while the winter crops had intermediate emission levels. The ranking based on IPCC guidelines (ADEME 2010) or modelled emission factors (O-CN) was somewhat different, with an overall lower range between crops (0.64 – 2.80 kg N_2O-N ha^{-1} yr^{-1} vs. 0.87-3.20 kg N_2O-N ha^{-1} yr^{-1}) : the highest emitter was winter wheat due to its high N input rate, while sugar-beet had low emissions because it received less fertilizer N. Indirect emissions due to nitrate leaching was several-fold higher with CERES-EGC than with the other methods.

	Winter wheat	Sugar Beet	Oilseed Rape	Fallow	Miscanthus on SB	Miscanthus on fallow
CERES-EGC :						
- direct	1.76	2.56	0.82	1.95	0.82	0.68
- indirect (leaching)	0.75	0.75	0.60	1.25	0.15	0.19
TOTAL	2.51	3.31	1.42	3.20	0.97	0.87
O-CN :						
- direct	1.96	1.30	1.78	0	0.49	0.49
- indirect	0.30[a]	0.13[a]	0.30[a]	1.25[b]	0.15[b]	0.19[b]
TOTAL	2.26	1.43	2.08	1.25	0.64	0.68
ADEME (2010)						
- direct	2.00	1.33	1.82	0	0.5	0.5
- indirect :						
residues	0.50	1.32	0.60	0	0.06[c]	0.06[c]
nitrate leaching	0.30	0.13	0.30	1.25	0.15[b]	0.19[b]
TOTAL	2.80	2.78	2.72	1.25	0.71	0.71

Table 5: Estimates of N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}) for the various feedstocks obtained with the simulation models (CERES-EGC and ORCHIDEE) or the IPCC 2006 guidelines as adapted by ADEME, 2010.

a : leaching from ADEME (2010)
b : leaching from CERES-EGC
c : residues left after removal of the miscanthus stand (below-ground N stock estimated at 100 kg N ha^{-1} in late spring ; Strullu, 2011).

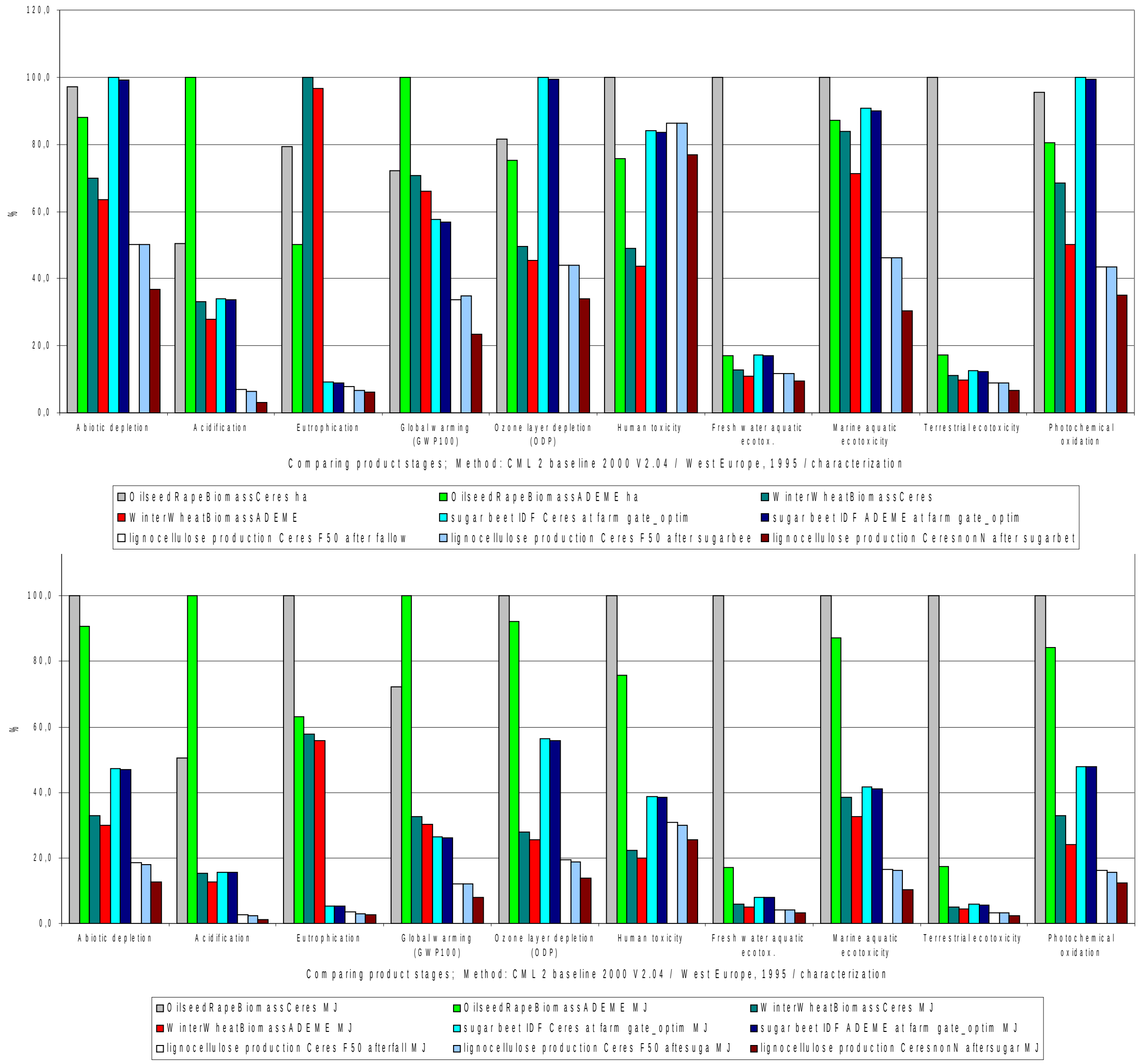


Figure 1. Cradle-to-farm-gate LCA results for the various feedstocks per ha (top) and MJ of biomass energy content (bottom). Indicators are normalized with respect to the feedstock with highest impacts. ADEME : field emissions taken from the ADEME (2010) LCA study on biofuels ; CERES : emissions output by CERES-EGC

Figure 1 presents the cradle-to-farm gate impacts of the various feedstocks investigated here, whether per ha of land or MJ of biomass energy content. Impacts per ha were 2 to 10 times higher with annual crops than miscanthus, while the ranking between the former crops varied across impact categories. Sugar-beet had the highest ozone depletion (OD), abiotic depletion (AD) and photochemical oxidation (PO) impacts, while oilseed rape had the highest global warming (GW) impact and winter wheat was had the highest eutrophication (EU) impact. Differences across crops were large for most categories, varying within a 1 to 4-fold range. The ranking per MJ was more consistent across impact categories : oilseed rape had systematically higher impacts, due to its low energy yield per ha, followed by winter wheat and sugar-beet, which achieved similar results, and miscanthus whose impacts were 5-fold lower than oilseed rape. There was a 20 to 100% difference between the impacts calculated with the ADEME emissions of Nr or CERES-EGC, in line with the differences noted in Table 5.

2. GHG balances and savings at whole-chain level

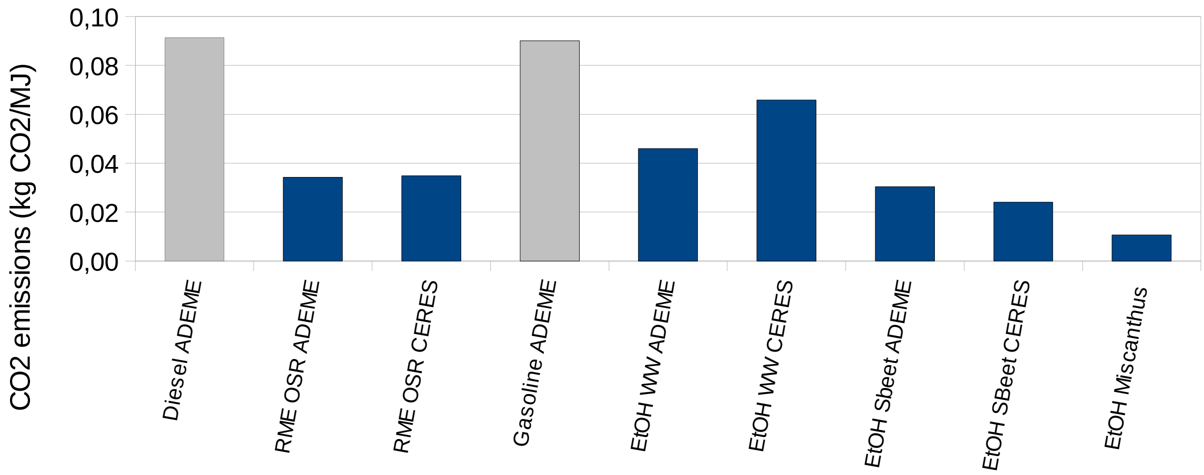


Figure 2. Life-cycle emissions of GHG per MJ of of biofuel the various pathways considered here and their fossil equivalents. EtOH : ethanol, RME : rape-methyl ester. ADEME refers to the ADEME 2010 study and methodology, as adapted to the Ile de France context ; CERES refers to the modelled emissions of Nr.

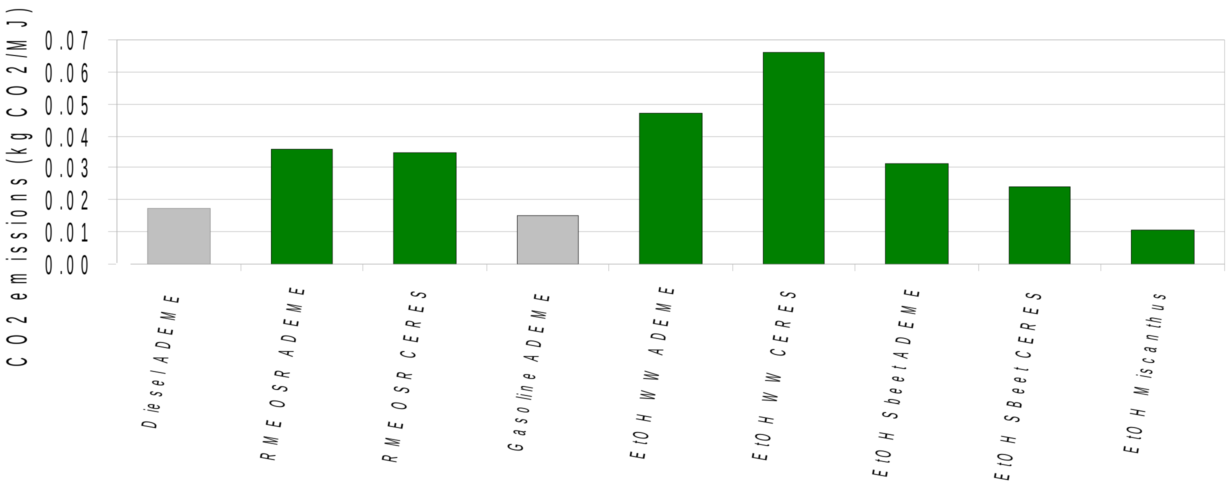
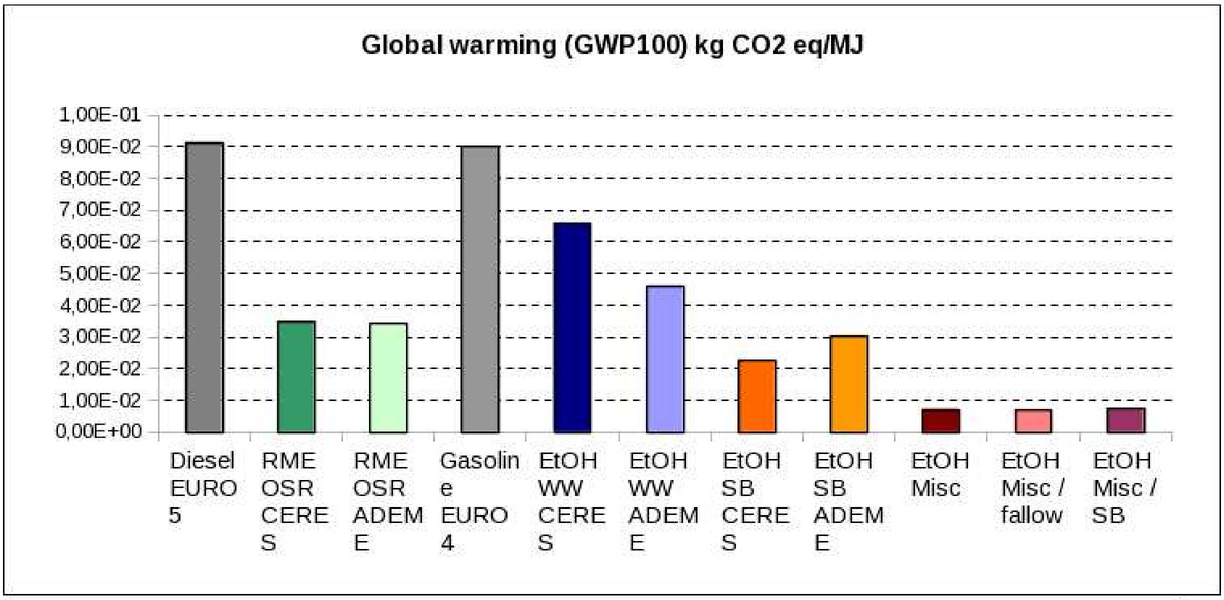


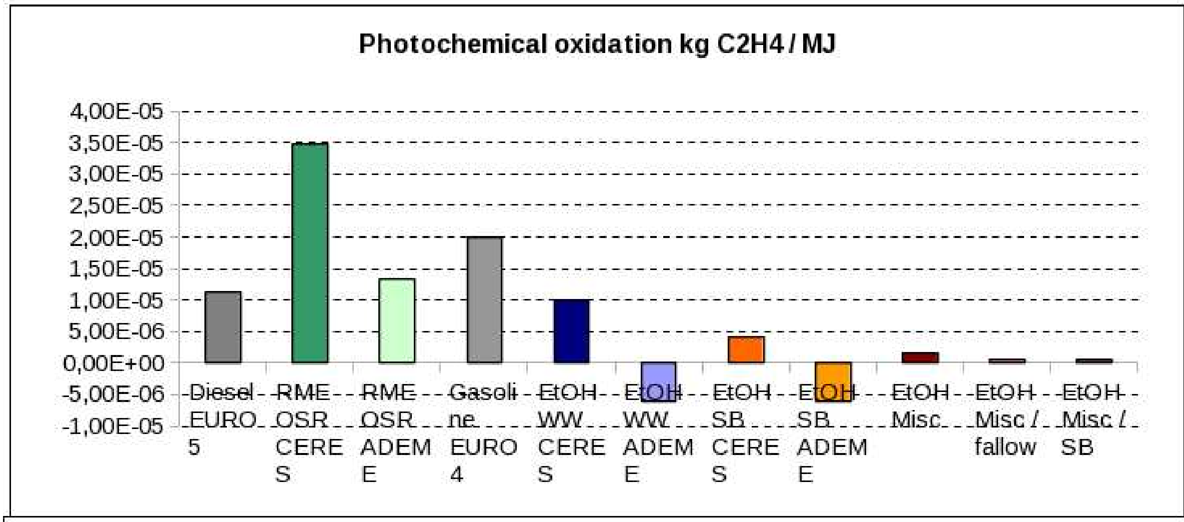
Figure 2 reports the GHG emissions of the various biofuels and feedstocks investigated in IMAGINE, compared to their fossile equivalents. Note that these are attributional LCA results, since indirect land-use change effects were not taken into account, and may incur extra emissions of CO2 (Fargione et al., 2008). All biofuel chains emitted less GHG than the fossile references, with savings ranging from 27% (ethanol from winter wheat) to 90% (miscanthus). There were significant differences between the LCA figures based on modelled field emissions (denoted CERES on Figure 2), which al and those based on default emission factors (ADEME) for the ethanol fuels. Life-cycle GHG emissions were 50% higher with the CERES scenario for winter wheat, and 15% lower for sugar-beet. The differences also arose from different management practices between the CERES scenario : it was first based on surveys specific to Ile de France when the ADEME data was representative of the whole of France. Secondly, it used system expansion in lieu of physical allocations for co-products. The relative balances between these methodological differences, resulting in either higher or lower GHG emissions between the ADEME and CERES scenarios, varied across biofuels, either mitigating or enhancing the differences in terms of N_2O emissions in the field (Table 5).

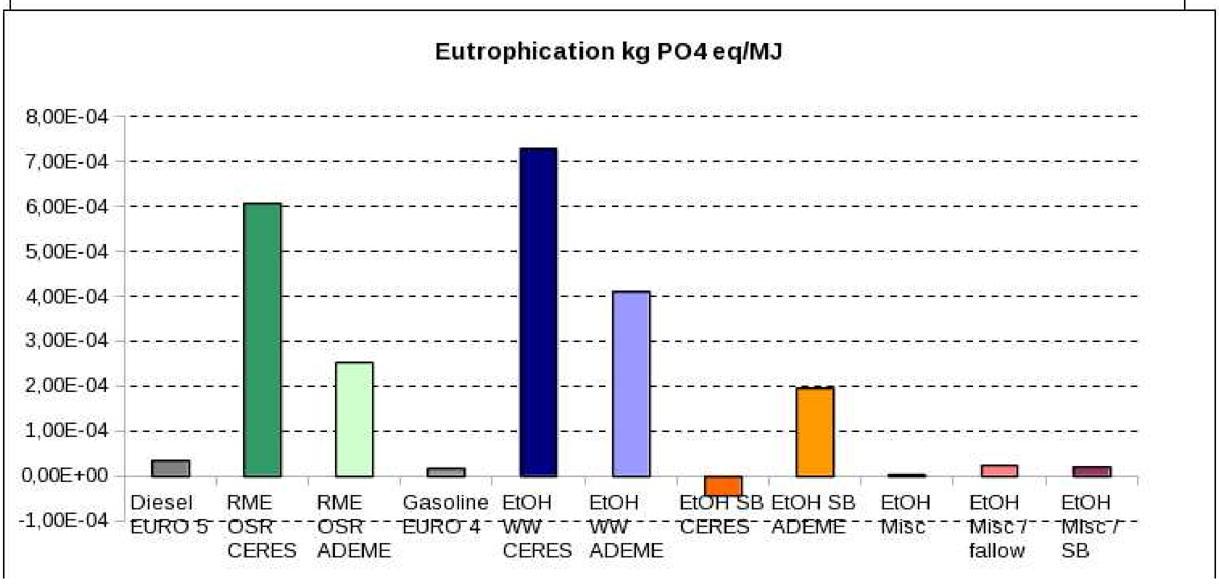
3. LCA results for bioenergy pathways

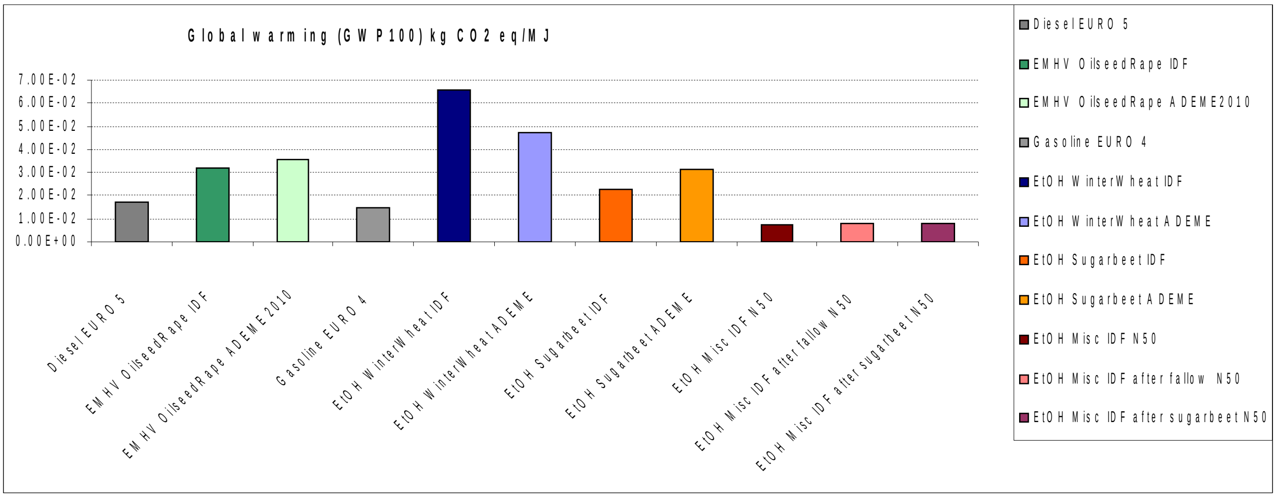
Figure 3 shows the LCA results for the other impact categories for the various biofuel chains. Overall, miscanthus had the lowest imapcts, whatever the land-use change sceanrios (after fallow or sugar-beet as an arable crop). The latter were much lower than the fossile references (for global warming or acidification impacts), or similar (for eutrophication). Negative impacts occurred for eutrophication with sugar-beet because of a credit in the system expansion which more than compensated for the direct emissions of nitrate in the field. The same occurred in the ADEME study with the sugar-beet and winter wheat ethanol pathways, although physical allocations were favoured. Similarly to the global warming impacts, bio-diesel from oilseed rape had the highest impacts for photochemical oxidation, and was on a par with winter-wheat ethanol for eutrophication. Sugar-beet ethanol thus emerged as the 1st generation biofuel with the best performance, but miscanthus ethanol was still much more efficient, except in the cases where 1st generation biofuels achieved negative impacts due to co-product credit. This net effect may however still be discussed.

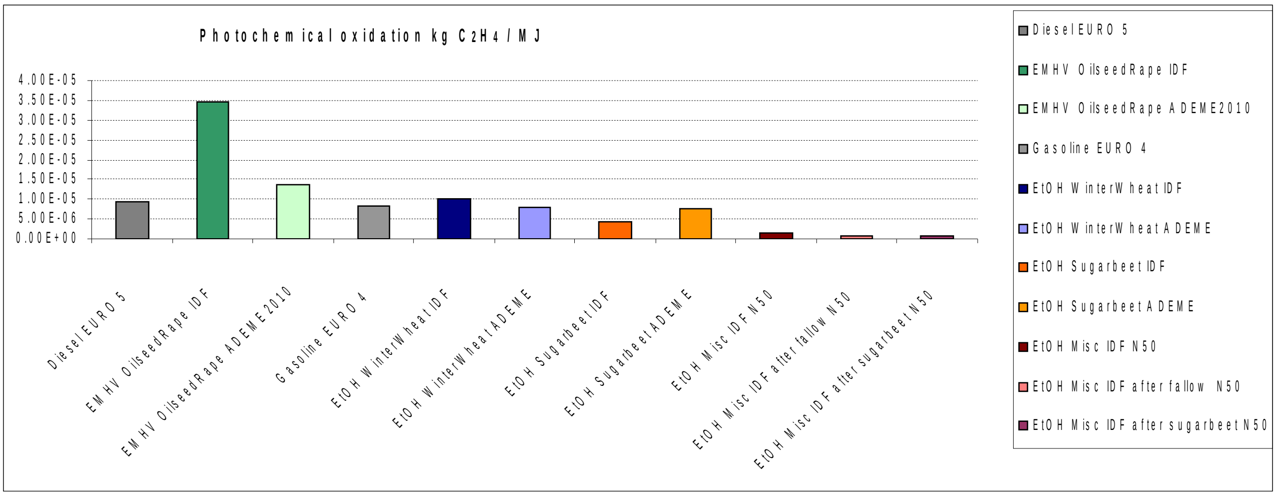
Figure 3. LCA impacts for the various bioenergy pathways and their fossil equivalents (gasoline for ethanol, diesel for bio-diesel). Same key as Figure 2 ; for miscanthus, 2 land-use change options were considered : establishment after fallow or sugar-beet (SB). In the baseline scenario (Misc), the crop was considered already established.

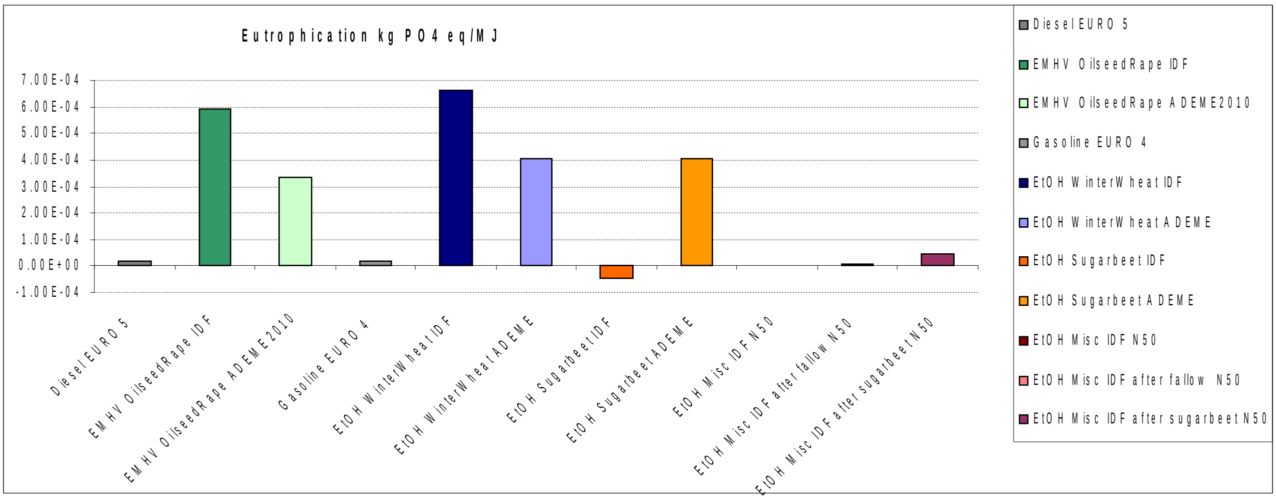


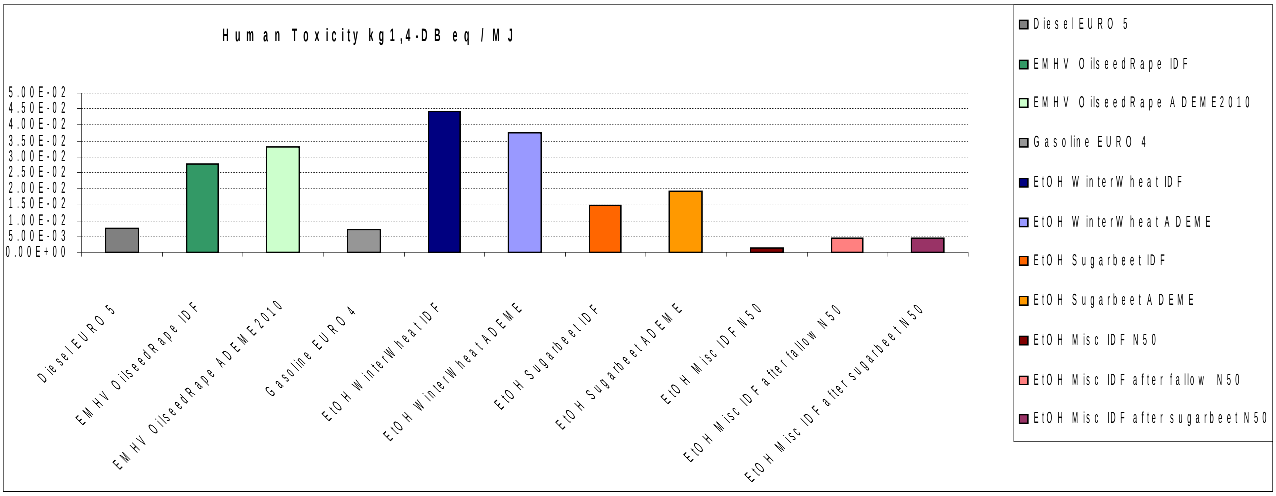





Global warming (GWP100) kg CO2 eq/MJ
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
Diesel EURO 5
EMHV OilseedRape IDF
EMHV OilseedRape ADEME2010
Gasoline EURO 4
EtOH WinterWheat IDF
EtOH WinterWheat ADEME
EtOH Sugarbeet IDF
EtOH Sugarbeet ADEME
EtOH Misc IDF N50
EtOH Misc IDF after fallow N50
EtOH Misc IDF after sugarbeet N50


Photochemical oxidation kg C2H4 / MJ
4.00E-05
3.50E-05
3.00E-05
2.50E-05
2.00E-05
1.50E-05
1.00E-05
5.00E-06
0.00E+00
Diesel EURO 5
EMHV OilseedRape IDF
EMHV OilseedRape ADEME2010
Gasoline EURO 4
EtOH WinterWheat IDF
EtOH WinterWheat ADEME
EtOH Sugarbeet IDF
EtOH Sugarbeet ADEME
EtOH Misc IDF N50
EtOH Misc IDF after fallow N50
EtOH Misc IDF after sugarbeet N50


Eutrophication kg PO4 eq/MJ
7.00E-04
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
-1.00E-04
Diesel EURO 5
EMHV OilseedRape IDF
EMHV OilseedRape ADEME2010
Gasoline EURO 4
EtOH WinterWheat IDF
EtOH WinterWheat ADEME
EtOH Sugarbeet IDF
EtOH Sugarbeet ADEME
EtOH Misc IDF N50
EtOH Misc IDF after fallow N50
EtOH Misc IDF after sugarbeet N50



4. Conclusion

The WP resulted in a regionalized, multi-criteria profile of the environmental impacts of a set of biofuel pathways, based on either or perennial annual crops.

5. References

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